Orbital Drag - Atmospheric Density Concept of Operations 2004 Update

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This paper presents the current, near-term, and future Concept of Operations (CONOPS) for using space-based observations in satellite orbital drag specification and prediction. The Concept of Operations was used for neutral density requirements refinement for the National Polar-orbiting Operational Environmental Satellite System (NPOESS). This concept resulted from interaction with various user groups and atmospheric density modelers.

Nomenclature

A_p	=	daily planetary geomagnetic index
$F_{10.7}$	=	solar index based on 10.7 cm radio flux

I. Introduction

THIS work was performed in support of the National Polar-orbiting Operational Environmental Satellite System (NPOESS) Integrated Program Office (IPO). NPOESS is the integrated satellite program scheduled to replace the current Defense Meteorological Satellite Program (DMSP) and Polar-orbiting Operational Environment System (POES) in the latter part of this decade. The Space Environment Sensor Suite (SESS) is one of seven major

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payloads currently under development within the NPOESS program. SESS has been assigned 11 NPOESS Environmental Data Records (EDRs) for assessing the space environment in terms of neutral and charged particle backgrounds, electric and magnetic fields, and optical signatures of the aurora. The SESS will use a synergistic complement of sensors and algorithms to measure and process data on the near-Earth space environment. The advanced capabilities for the NPOESS will provide operational Space Weather users with significant upgrades to heritage sensor design, as well as significantly increased data volume and improved data latency over that which is presently available.

The concept documented in this paper is an update to a joint NPOESS/Air Force Space Command (AFSPC) study completed in 1998 to understand and document end user needs for space weather information. The purpose of the 1998 assessment was to critically evaluate user needs for space environmental data within the context of a potentially affected system. Such systems may operate either within space (satellites), through space (radar), or coupled to space (power grids). The "user" is not considered to be a service provider such as the Air Force Weather Agency (AFWA) or the NOAA Space Environment Center (SEC) but, rather, the end user. For the NPOESS, the applicable user needs are those specified by the DoD, the DoC, and NASA. Within the context of this understanding, the following activities were performed:

1) Develop a list of the users of space environmental data within the military and civilian communities,
2) Assess mission impacts and sensitivities to the space environment,
3) Detail whether current space environmental data products are used directly or as inputs to models whose outputs are subsequently used,
4) Survey user satisfaction with space environmental data products currently available and expectations for future products.

The study then defined that set of space environmental data products and services that must be supplied to the end users by the Space Environmental Support Architecture (SESA). This architecture includes both the space environment specification and forecast agencies; that is, the AFWA and the SEC, and tactical users. The SESA includes all the resources and facilities needed to collect, process, and disseminate space environmental data products and services. The specification and forecast agencies require input data from a variety of sources which include NPOESS and other space-based and ground-based space environmental sensing platforms. This included the following activities:

1) Document existing CONOPS within the SESA to satisfy user needs for space environmental products,
2) Identify changes to existing CONOPS that will improve user support within a revised SESA,
3) Determine which space environmental products in the revised SESA should be allocated to the NPOESS,
4) Identify which, if any, of the current NPOESS space EDRs can be better met by other space and ground sensing platforms.

The primary output product delivered to the NPOESS IPO was a re-validated and revised list of EDRs for space environmental sensing, based on the various Concepts of Operations.

In order to accomplish the activities listed above, three mission sub-groups were formed: ionospheric, spacecraft anomaly detection, and orbital drag. The authors of this paper are the team of orbital drag/atmospheric density application, requirements, and modeling experts that comprised the orbital drag sub-group. Reference 1 provides the results from the two other mission sub-groups.

It is important to understand that the CONOPS presented in this paper was not limited to what NPOESS could provide to the user. Because the original study was a joint effort between a program office and user group, the resulting concepts attempted to include all users, processing centers, and means of collecting the needed data (e.g., ground and space-based). Appendix A contains the CONOPS produced by the orbital drag sub-group for the 1998 study.

In 2004, Under Secretary of the Air Force Peter Teets directed that an Independent Assessment (IA) be performed to determine if the proposed NPOESS SESS architecture is less capable than the operational systems it will replace (i.e., DMSP and POES). This assessment was comprised of the following activities:

1) Describe the operational benefit provided by each space environmental parameter
2) Document how sensor data is converted to usable operational products, and
3) Document how the operational products are used by operators of civil and military systems to enhance their mission or mitigate impacts.

The approach taken to complete these activities was to update the 1998 CONOPS. The orbital drag sub-group reconvened and updated the CONOPS that was produced six years ago.

II. Background

A. Objective

The objective of this paper is to document the updated Concept of Operations. In order to meet this objective, the team revisited the 1998 concept – the data, models, and methods that were assumed.

B. Applications

In general, the user requirement for orbital drag is actually a requirement for satellite ephemeris accuracy. The users concerned with orbital drag are the Cheyenne Mountain Operations Center (CMOC) Space Control Center (SCC), National Reconnaissance Office, NASA Marshall Space Flight Center, and the Alternate SCC (Dahlgren, VA), as well as other select satellite owners/operators.

The SCC is responsible for maintaining a catalog of ~10,000 resident space objects. The SCC ingests position and velocity observations from ground and space-based surveillance sensors and maintains precise positional and velocity information on each object. The SCC also predicts future positions in support of user applications. The application areas are as follows: 1) highly accurate orbit prediction in support of satellite rendezvous, precision targeting, pointing for scientific systems, and positional information on special interest satellites; 2) collision avoidance for the International Space Station and other high interest objects and for determination of launch windows; and 3) orbital lifetime and reentry prediction. Since there are several ways to obtain increased orbital ephemeris accuracy, the user needs specified for NPOESS were framed in terms of a neutral density profile (NDP) specification to facilitate improvements in orbital propagation models. At the time of the original assessment, there were a large number of users of the General Perturbations (GP) orbital ephemeris determination and prediction, which uses a crude fitting scheme for the NDP. However, the space object catalog is now transitioning to having all objects maintained using the Special Perturbations (SP) propagation model, which requires a complete neutral density model. Since the SP processing invokes the use of empirical operational density models, the reliance on atmospheric density specification and prediction has increased over the past 6 years.

The basic challenge with the specification of neutral density is that the connection between the orbital prediction requirement and neutral density accuracy has not been fully quantified. Orbital prediction accuracies are implicit in the standoff requirements for debris in Space Station operations. Yet the density accuracy requirements corresponding to these standoff distances cannot be easily quantified, since they depend on the period of trajectory prediction, the specific orbital characteristics, and the value and stability of the satellite's ballistic coefficient (a measure of how much a satellite is affected by atmospheric drag). Similarly, requirements for reentry prediction exist, but the sensitivity of neutral density errors compared to other uncertainties has not yet been quantified. However, it is believed that stressing requirements will emerge from the need to maintain a large catalog of space objects, address collision avoidance concerns, and provide more accurate reentry predictions.

C. Requirements Investigation and Validation

The original CONOPS relied on the best available requirements documentation at the time. Since the Space Control Capstone Requirements Document (CRD) [2] had not been published, we performed a requirements validation that entailed meeting with the space surveillance/space control community in order to investigate and validate end user requirements for orbital drag and neutral density accuracy. We met with a variety of users, including CMOC SCC operators, AFSPC Space Warfare Center (SWC) personnel, whose job it is to provide astrodynamic support to CMOC, MITRE, and various contractor personnel.

This validation produced the following threshold and objective accuracy (standard deviation) requirements for a neutral density profile that were used to define the CONOPS needed to obtain these values:

Altitude	Threshold	Objective
<500 km	10%	5%
500-700 km	15%	10%
>700 km	20%	15%

The ability to accurately quantify and predict neutral density in stressing solar and geomagnetic conditions is limited by the ability to accurately predict solar and geomagnetic activity, as well as the precise relationship of geomagnetic activity to the response of the neutral density field. Presently, prediction skill is modest for solar activity and marginal for geomagnetic activity [3]. We believe that efforts to improve drag prediction should be coupled with efforts to better characterize solar and geomagnetic activity and improve their prediction, and efforts to improve physical forecast models.

An important update occurring over the past 5 years is the increased emphasis on ephemeris specification and prediction accuracy. Stringent (and classified) requirements documented in a March 2000 Space Control CRD led to a desire to meet the objective uncertainty requirement. The CRD established requirements for orbital accuracy at epoch and at 18 hours prediction time from epoch. For the updated CONOPS, we compared the CRD values with the above values, and noted that the CRD requirements are more stringent than those documented in the original study. Thus, the need for the far-term CONOPS, which addresses the objective requirements, is heightened.

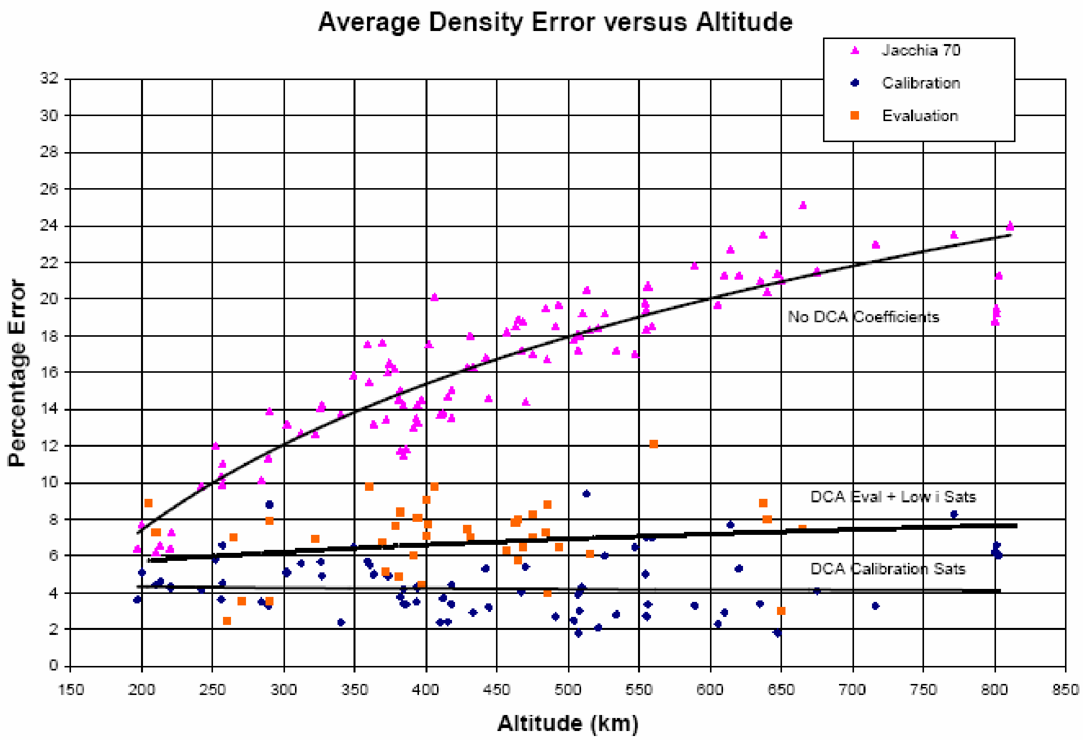

Figure 1. Empirical model vs. HASDM density error [4]

D. Baseline Performance

Current empirical neutral density models that are used at the operational centers (e.g., Jacchia 70) have density errors that vary depending on the satellite orbit characteristics and are reflected in the variability of the satellite's ballistic coefficient. For Figure 1, the ballistic coefficients are computed with only a two-day temporal resolution. Even at this coarse resolution, the typical density errors reflected in the standard deviation of the ballistic coefficients (normalized with respect to the ballistic coefficient for each satellite) are as high as 24% at an altitude of 850 km for the standard Jacchia 1970 model (J70). Since the variability of the ballistic coefficients is roughly Gaussian in nature, a standard deviation of 24% means that about 68% of the two-day averaged density errors are less than 25%, and about 32% of the two-day averaged density errors are greater than 24%. Since many other effects, other than density error, contribute to the variability of the estimated two-day ballistic coefficients, the actual two-day averaged density error is probably somewhat less than what appears in Figure 1. However, the point-to-point density errors are considerably larger, due to unmodeled local density features.

In the past 5 years, there has been a breakthrough in improvement of operational density specification accuracy. Since September 2004, the High Altitude Satellite Drag Model (HASDM) [4] has been used in the SCC. This approach was based on the concept originating from AFRL [5]. HASDM has shown the capability to assimilate orbital drag data and to reduce specification errors through empirical means. HASDM includes an empirical time series prediction algorithm for predicting the Dynamic Calibration Atmosphere (DCA) correction coefficients (i.e. global density field) out 3 days. DCA is the algorithm that estimates neutral density corrections to the Jacchia model, based on the behavior of many (~80) low-perigee satellites and space debris.

Figure 1 shows how the average density specification error (standard deviation) changes with satellite perigee altitude. Each data point is the standard deviation in the variation of the two-day satellite ballistic coefficient relative to the average ballistic coefficient for a particular satellite. This figure indicates that, with Jacchia 1970 (current operations), the SCC does not typically meet the objective, nor the threshold requirements for atmospheric density accuracy, except for altitudes below 250 km, where they typically meet the threshold requirement of 10%, due to the small thermospheric variations at these altitudes. With the implementation of HASDM's DCA, the SCC should typically meet threshold requirements within the altitude range of Figure 1. Only for the calibration satellites are the standard deviations typically below the objective of 5%. Therefore, the inclusion of HASDM at the SCC is providing two-day averaged density errors with typical standard deviation of ~8% or less at epoch.

As one approaches lower altitudes (90-120 km), the density and associated error can vary drastically, especially during times of higher geomagnetic activity, even though the average density error appears to be relatively small. It's important for operations to improve the ability to accurately model density in the altitude range 90-120 km for reentrant objects, Molniya satellites, and other very low perigee objects, especially if the perigee lies in or near the auroral zone. Even at 850 km, the typical error rises to only 8% with HASDM.

With the use of HASDM, 65-70% of the high-drag satellites in the object catalog are meeting the CRD requirements. However, the requirements are not being met consistently, either at epoch or for predicted positions. HASDM's initial results show that it works well for "quiet" periods of time. However, during storm conditions, there is still a need to go beyond a technique of this sort in order to specify the neutral atmosphere to within the stated uncertainty requirements. Additionally, HASDM uses only a crude empirical method to forecast density.

The current planetary geomagnetic index is seriously deficient for measuring the amount of Joule heating and particle precipitation heating affecting the neutral and ionospheric densities. Having real-time data on these geomagnetic storm heating patterns is essential, since the patterns vary dramatically from storm to storm and throughout any individual storm. The shape and intensity of these different patterns drive the thermosphere-ionosphere dynamics and density very differently. Hence, today's systems and models are not meeting user requirements.

E. Orbital Drag Support

Figure 2 depicts the traceability from user missions to requirements to products that a space-based platform can provide to satisfy the requirements. The Concept of Operations defines how the products can be processed to meet the user needs.

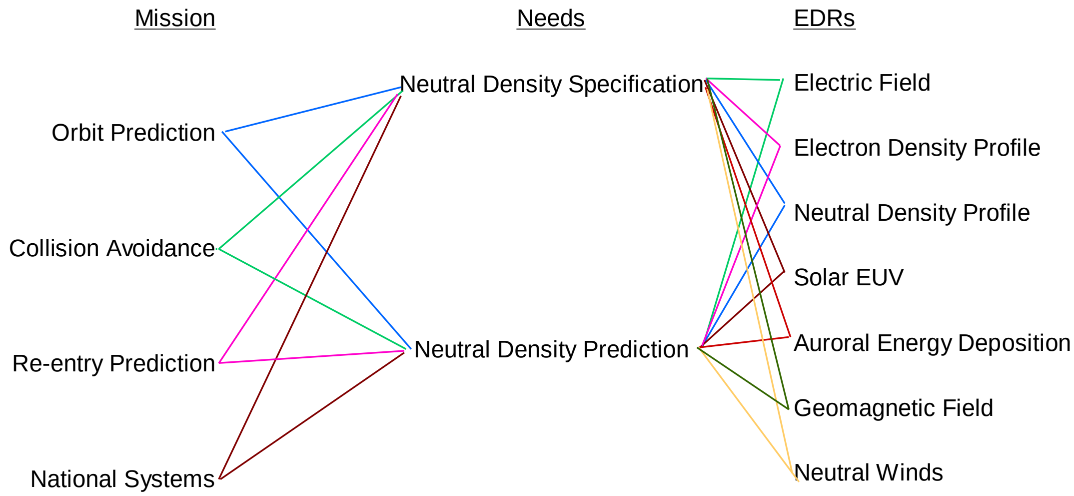

Figure 2. Traceability of User Mission to User Needs to Space-based Sensing Data Requirements

III. Concept of Operations

This section documents the concepts for current, near-term, and far-term operations. The team considered a variety of ideas to improve density specification and forecasting in support of orbit determination. One such method is the use of a neural network technique [6]. Another idea we considered is direct ingest of solar Extreme Ultraviolet (EUV) data into operational density models. Although these methods have merit, the team decided on the chosen concepts as the most feasible to implement with the greatest degree of promise for improving orbital prediction accuracy via density improvements.

The current CONOPS relies on ground-based sensors to provide proxy values of solar and geomagnetic activity to empirical density models. In addition, space surveillance tracking data is used to enhance the density specification through the use of HASDM. The near-term CONOPS includes the current operations with the addition of far Ultraviolet (UV) airglow data from DMSP being used to improve the density calculation.

The future CONOPS introduces an assimilative process and physics-based modeling that relies on space-based products to enhance the operational empirical models. Ideally, the physics-based model would provide a global specification and forecast to the operational centers that would replace the empirical models. Except for short-range predictions, significant advances will depend on the combination of first-principles models coupled with increased skill in predicting geomagnetic and solar activity. It is crucial that the future model be both physics-based and assimilative.

A. Current (2004-2006)

The current CONOPS is illustrated in Figure 3. The solar and geomagnetic proxy data from the ground-based sensors are being used today as input into the empirical density models at the user locations. For the current CONOPS, we include DMSP as a sensor, since the far UV sensors (Special Sensor Ultraviolet Spectrographic Imager (SSUSI) and Special Sensor Ultraviolet Limb Imager (SSULI)) are on the F16 spacecraft that is undergoing on-orbit calibration and validation. This data should be provided operationally within the next year. However, the SSULI instrument has recently undergone a Tiger Team investigation due to unacceptable levels of noise in the data for portions of the spectrum. If the noise is not reduced, then the neutral density profile features for SSULI on F16 may not be useable. However, SSUSI is producing retrievable data. The Global UV Imager (GUVI), a predecessor instrument to SSUSI, has shown promising, though limited, comparison to orbit-based densities.

Current operations at the SCC rely on HASDM for improved density specification. Section IID provides details on this model.

The users would like to have density correction factors based on the space-based sensor data provided to them. If these factors were available, they would be used to correct the empirical model. However, the creation of these correction factors is not part of the baseline processing for the central processing center. Section IIID provides more information on this processing disconnect.

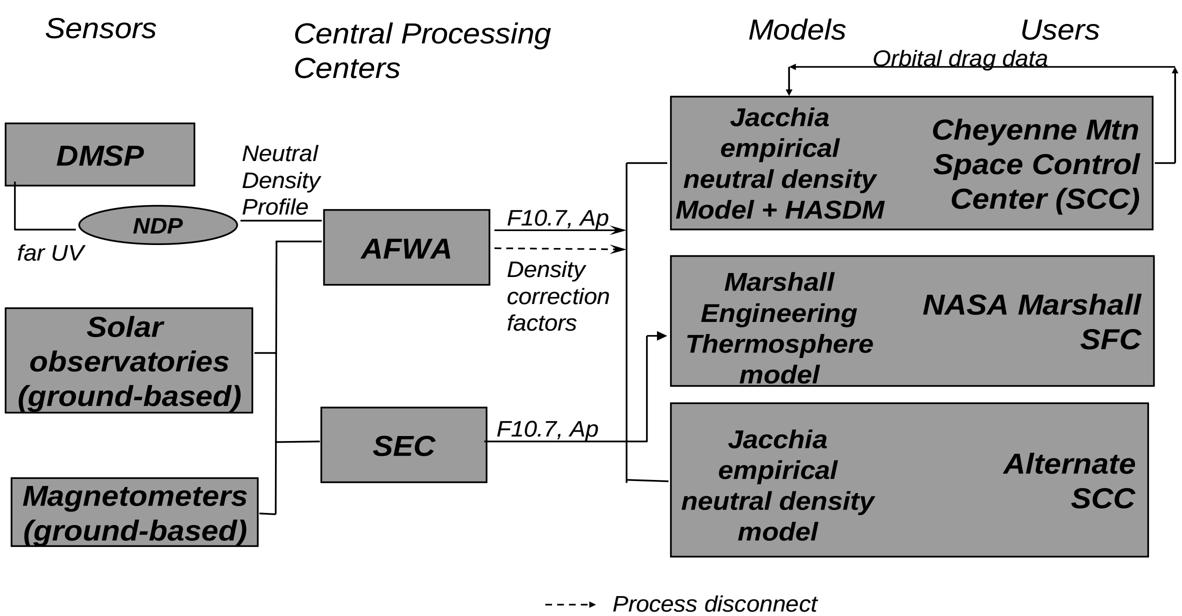

Figure 3. Current Concept of Operations (2004-2006)

B. Near-term (2006-2011)

Figure 4 depicts the near-term Concept of Operations. The proposed near-term concept is to use the DMSP far UV data to correct a global specification model (NRLMSISE-00 or similar). Optimal model input parameters and output density scaling factors would be produced and sent to the operational centers. The SCC, as an example, could utilize a weighting scheme that uses the NRLMSIS correction factors for altitudes that have sensor data (typically 250-400 km), and uses the HASDM correction factors outside of this altitude range. The timeframe for the near-term CONOPS was chosen based on NRL's plan to transition the use of far UV data into operations.

It is assumed that the process disconnect noted in the current CONOPS will be corrected in the near-term. The central processing center (AFWA) will assimilate the far UV data from DMSP into a model and produce density correction factors.

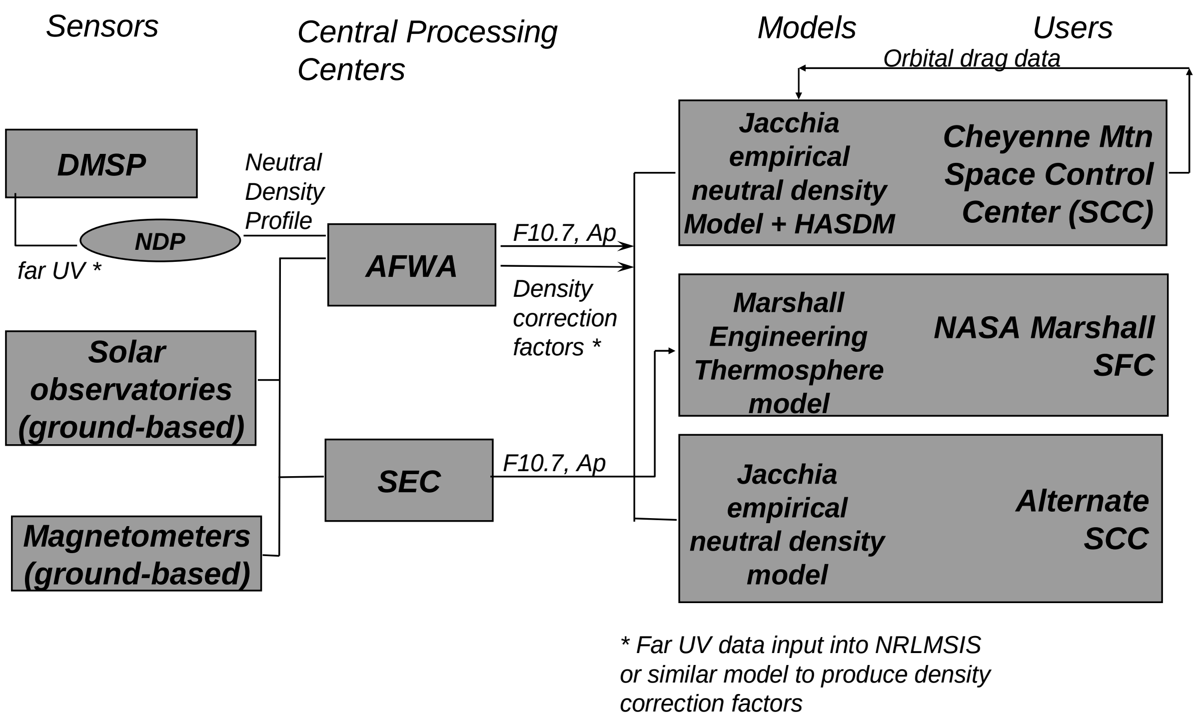

Figure 4. Near-term (2006-2011) Concept of Operations

C. Far-term (2011 and beyond)

Figure 5 depicts the far-term Concept of Operations. For this CONOPS, the NRLMSIS or similar model would be replaced with an assimilative process using a physics-based model. This future thermospheric model would, by nature, be predictive. It is likely this would be a coupled thermosphere-ionosphere physical model. Ideally, the output product sent from the processing centers (AFWA and SEC) to the user would be a global atmospheric specification and forecast product that would replace the density models resident in the operational centers. The timeframe for the future CONOPS is based on modelers' experience with length of time to transition a research model into operations. Also, more development is needed to improve the assimilative sub-models discussed further in this section.

A physics-based model will not be able to consistently meet the 'goal' of less than 5% density error at all altitudes unless it has sufficient real-time space weather data to input to the model. The space weather sensors proposed for NPOESS are essential for providing some of the necessary data to drive the proposed physical model. Coupled physical models of the thermosphere and ionosphere need measurements of each of the individual neutral gas species to be provided by the far UV sensors. The physical models need this data collected from as many orbital planes as practical.

There is a need to develop an assimilation scheme that can be used to initialize physics-based models. Specification schemes that are appropriate for drag calculations are not necessarily appropriate for initialization purposes. The optimal assimilative process and physics-based model are a subject of ongoing research. One possible solution is to adjust the physics-based model parameters so that its density field agrees with the HASDM or NRLMSIS field. This is analogous to the way a GPS receiver is coupled with an altimeter to produce a more accurate measure of altitude than either instrument could do by itself. HASDM acts like a GPS receiver, thus providing a low-resolution calibration that is accurate in an absolute sense, whereas the physics-based model acts like an altimeter, thus providing high-resolution information that is accurate in a relative sense.

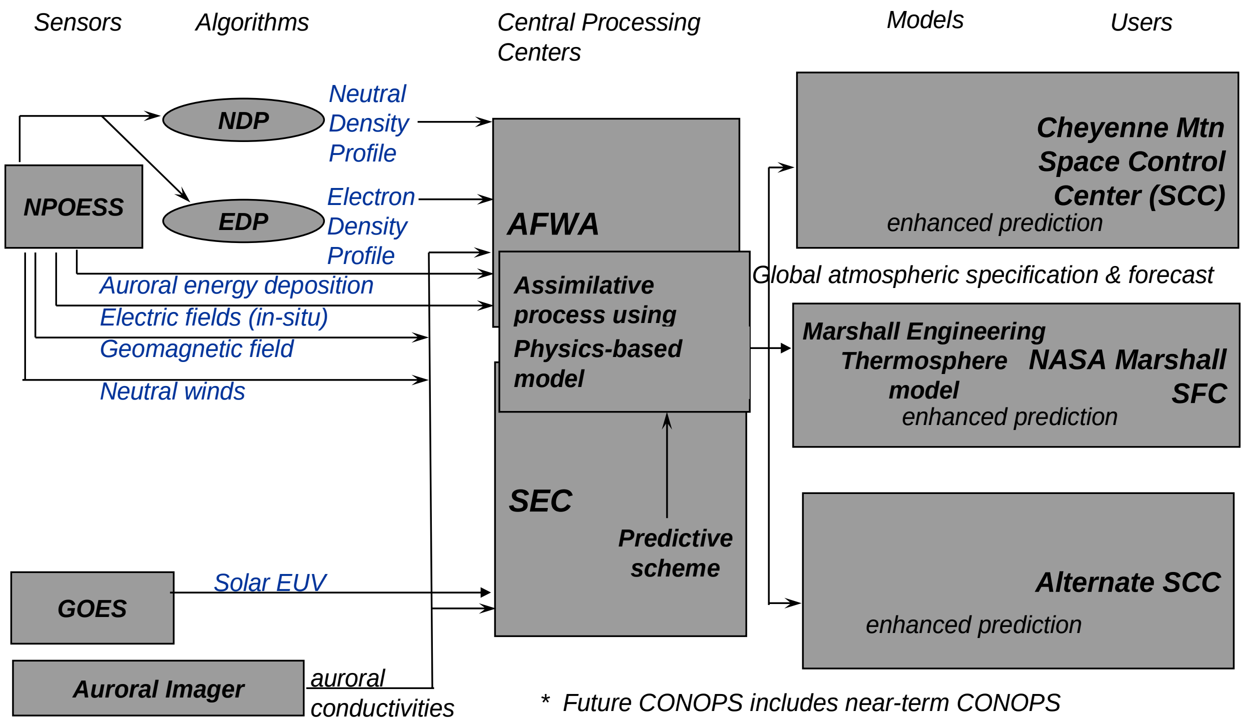

Figure 5. Far-term (2011 and beyond) Concept of Operations

University of Colorado researchers based at NOAA/SEC are currently developing a physical model Kalman filter that could be used to complement HASDM in the future. This research team is also involved with the Global Assimilative Ionospheric Model (GAIM) and is responsible for developing the neutral atmosphere composition component to it. This model will use NPOESS data as input to determine the neutral composition.

The requirements for EDRs related to first-principles models were based on modeling experience and the best judgment of first principles modelers. The following paragraphs provide detail on how the products from NPOESS, GOES, and other satellite platforms would be used in the physics-based model.

<u>NEUTRAL DENSITY PROFILE/IN-SITU DENSITY</u> In order to meet objective requirements, it is necessary for the physics-based model to be initialized by neutral density data with accuracies that are commensurate with the objective requirements themselves.

The team recognizes that there is a challenge in meeting the accuracy requirements throughout the specified altitude range with current technology instruments (i.e, SSUSI/SSULI). These instruments remotely measure airglow at altitudes up to around 350 km. The rest of the profile information needs to be extrapolated from the remotely-sensed data, and the estimated uncertainty obtainable at these extrapolated altitudes is 20%. By providing an *in-situ* measurement of total neutral density (at NPOESS altitude of 850 km), an interpolation scheme could be used to provide better accuracy. The use of the *in-situ* data in this way is a subject of further study.

In addition, individual composition information is needed to meet the objective accuracy requirement of 5% density accuracy error through use of physics-based models. The first principles models needed to satisfy objective requirements are necessarily multi-constituent models. The *in situ* measurements are likely to be more accurate than remote measurements and provide a reference for neutral density inferred from airglow. The total mass density at NPOESS altitudes is essentially due to O and He, and the remote sensors will not obtain He composition information. However, *in situ* measurements at NPOESS altitudes were deemed less important than global measurements over a range of altitudes made by remote sensing. *In-situ* composition data could be measured from space by a mass spectrometer. However, this instrument is not part of the baseline payload for NPOESS and represents a significant increment with respect to cost.

ELECTRON DENSITY PROFILE The electron/ion densities, along with neutral densities, are important for initializing a coupled thermosphere-ionosphere physical forecast model. The electron/ion density measurements are also related to the need to specify the magnetospheric energy input to improve the driver of empirical and physics-based models. Electron/ion density distributions are required to calculate heat and momentum sources for the neutral upper atmosphere, specifically, they are required to calculate ionospheric conductivities for Joule heating and ion drag. The primary atmospheric heat source of magnetospheric origin is Joule heating, which is calculated from the product of Pedersen conductivity and the square of the electric field. The electron/ion density distribution provides Hall conductivity to invert ground-based magnetometer measurements, and provides Pedersen conductivities for direct input to the Joule heating calculation. The required accuracy for electron density is a function of the sensitivity of Joule heating to electron density, on the one hand, and the heating accuracy required to meet objective neutral density requirements, on the other.

It is important to have the horizontal distribution of ion density as well as vertical profiles (i.e., a three dimensional distribution). Vertical profiles along the satellite track are useful, but the three-dimensional distribution greatly adds to the value of the measurements. This is because it is necessary to specify the three-dimensional distribution of ion density to perform first principles simulations. In the absence of measurements of the horizontal distribution, there would be a reliance on statistical models to provide the necessary coverage.

AURORAL ENERGY DEPOSITION Charged particle fluxes are required to calculate particle (kinetic) heating and ionization rates of the neutral upper atmosphere. The amount of heating depends on the total energy flux and the altitudes where it is deposited. The latter is a function of the characteristic energy. Maps of characteristic energy and column energy deposition rates would be more valuable than *in situ* measurements of particle energy spectra (although having both would be desirable). The values for column rates need to be augmented with values for the characteristic energy.

ELECTRIC FIELDS Electric fields are required to compute Joule heating and ion drag. The required accuracy for electric fields is a function of the sensitivity of Joule heating to electric field strength and the heating accuracy required to meet objective requirements for density accuracy. There is a need to have high-resolution measurements in the auroral region and a necessity to include non-auroral sources to satisfy objective requirements.

GEOMAGNETIC FIELD In addition to auroral energy deposition and electric field data from NPOESS to derive Joule heating rates, information can also be provided by magnetometer data. The magnetometer is a measure of the effective current flow into and through the upper atmosphere, and provides information on the Joule dissipation. The current flow implicitly includes the effect of the neutral winds in the dissipation, so it is complementary to other measures of the electrodynamics.

NEUTRAL WINDS For physics-based models, wind data is valuable. The drag force is related to the velocity of the satellite (or debris) relative to the wind velocity. At high latitudes during disturbed conditions, winds can be a 20% effect relative to no-wind conditions. Upper atmosphere winds can be measured from space using passive optical instruments (e.g., Fabry Perot Interferometers) that measure Doppler shifts in airglow emissions. These instruments are not part of the baseline payload for NPOESS and represent a significant increment with respect to cost and demands on satellite resources. Also, the utility of wind measurements is uncertain, pending further study.

SOLAR EUV The extreme ultraviolet portion of the solar spectrum is responsible for creation of the Earth's ionosphere, as well as most of the heating of the thermosphere and exosphere. Solar EUV radiation is totally absorbed in the upper atmosphere and must be measured from space. Except during large magnetic storms, most of the energy that heats the upper atmosphere comes from the absorption of solar EUV radiation. Present models of upper atmospheric density rely on imperfect proxies of solar EUV (sunspot number, $F_{10.7}$). Proxy accuracies are insufficient to meet objective requirements. The EUV heating of the upper atmosphere is a function of the product of the EUV flux per wavelength interval and the interval-averaged cross sections (absorption, dissociation and ionization) summed over the EUV spectrum. The coverage, resolution, and accuracy for solar EUV are based on the sensitivity of heating to EUV fluxes and the sensitivity of density to heating. It might also be possible to use EUV measurements to improve empirical models by replacing the current proxies for EUV. However, this is complicated by the fact that the historical databases for empirical models that correlate EUV proxies and density are very sparse, and the corresponding EUV data is generally not available.

AURORAL CONDUCTIVITIES Auroral images can be used to infer the spatial structure and temporal variations in the auroral energy deposition and the consequent map of auroral conductivity. Ideally, images of magnetospheric or ionospheric convection should be combined with the conductivity maps to produce maps of Joule heating rates for input to the physical model. Unfortunately, imaging the ion convection is not yet feasible. The auroral conductivity maps from imaging are, however, ideal for interpreting the ionospheric current flow and electric fields from ground-based magnetometer networks. One of the few methods of improving on the empirical electric field maps to meet objective requirements is to combine electrodynamic information from ground networks and space-based observations using data assimilation methods such as Assimilative Mapping of Ionospheric Electrodynamics (AMIE)[7]. The auroral conductivity maps are an essential ingredient in the assimilation process.

D. Process Disconnect

A process disconnect was uncovered as the team was updating the CONOPS. We discovered that there is an inadequate process for the transition of research into operations for assimilative models. NOAA/SEC and AFRL are performing ongoing research to incorporate physical models into data assimilation. NRL researchers have also done work to establish ways to assimilate the far UV data provided by DMSP and NPOESS into operational density models. As stated previously, users require further enhancement attainable with a physical model. This is necessary in order to meet the requirements stated in the Space Control CRD. However, a comprehensive, formal research program and transition plan have not been established. Discussions are currently being held with AFWA to highlight this disconnect.

NRL has an ongoing 6.2 research project to investigate bringing the use of far UV data into operations. This entails adjusting the inputs and outputs of a global empirical density model like NRLMSIS to attain consistency with the far UV data. Model inputs and outputs would then be projected into the future to predict neutral density. NRL plans to have a demonstration of this operational at the ASCC in two years and have it ready for operation in four years. GAIM, planned for operation at AFWA in 2006, could be used as a paradigm for acquisition of an operational, global, coupled thermosphere-ionosphere physical model at AFWA.

IV. Conclusion

The importance of highly accurate atmospheric density specification and prediction has increased over the past 5 years. The emphasis on improved space situational awareness information has led to requirements for enhanced density models. HASDM has closed the gap between user requirements and current capabilities for density specification. However, in order to meet user needs for density specification under all solar and geomagnetic conditions, as well as to satisfy the needs for forecasting, an assimilative process relying on physics-based techniques is required.

A formal, comprehensive research program and research-to-operations transition plan are needed in order to assure these new processes and models become operational.

Appendix

This appendix contains the CONOPS from the 1998 Concept of Operations study. Note that what the team predicted six years ago for the near-term CONOPS has actually occurred, and the near-term concept from the 1998 study is now the current CONOPS for the updated study. The 1998 concept continues to be the future concept for the updated study.

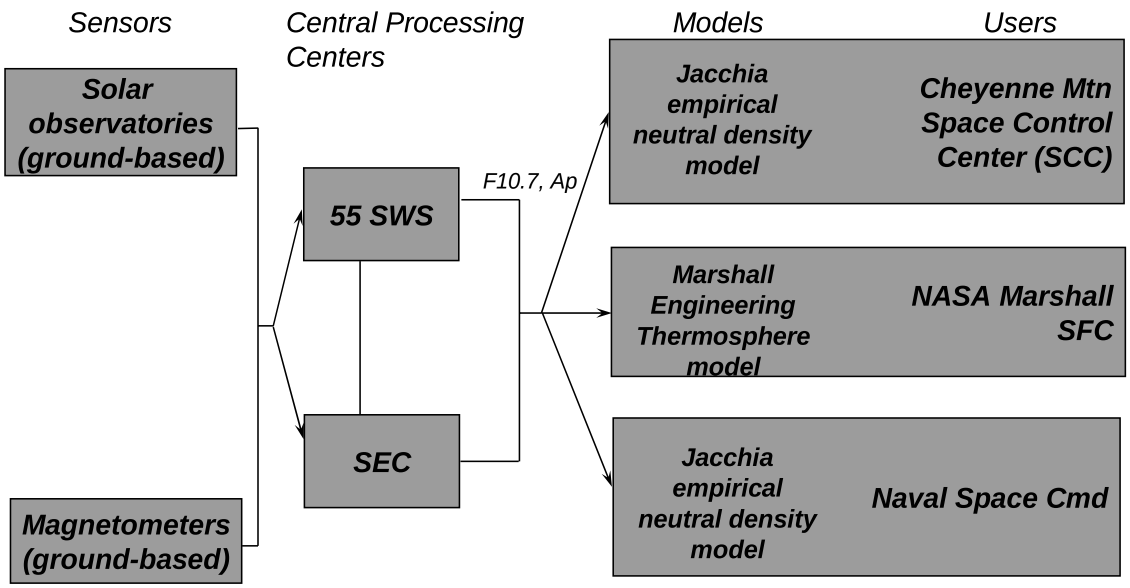

Figure 1A. Current Concept of Operations (1998 study)

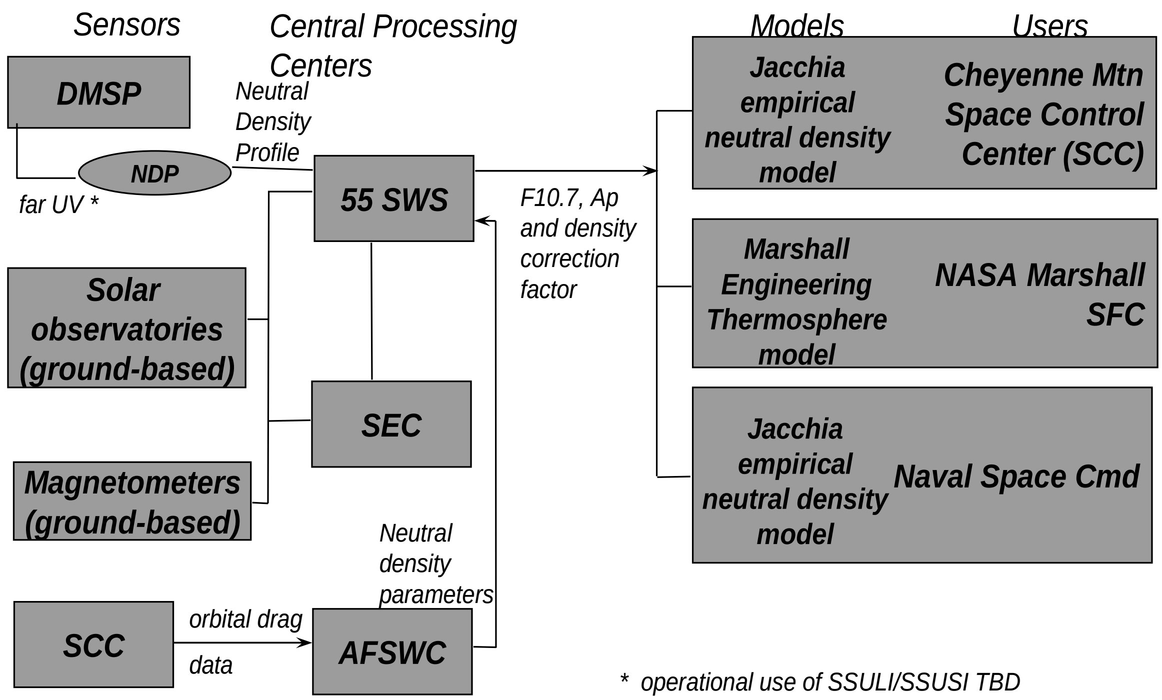

Figure 2A. Near-term Concept of Operations (1998 study)

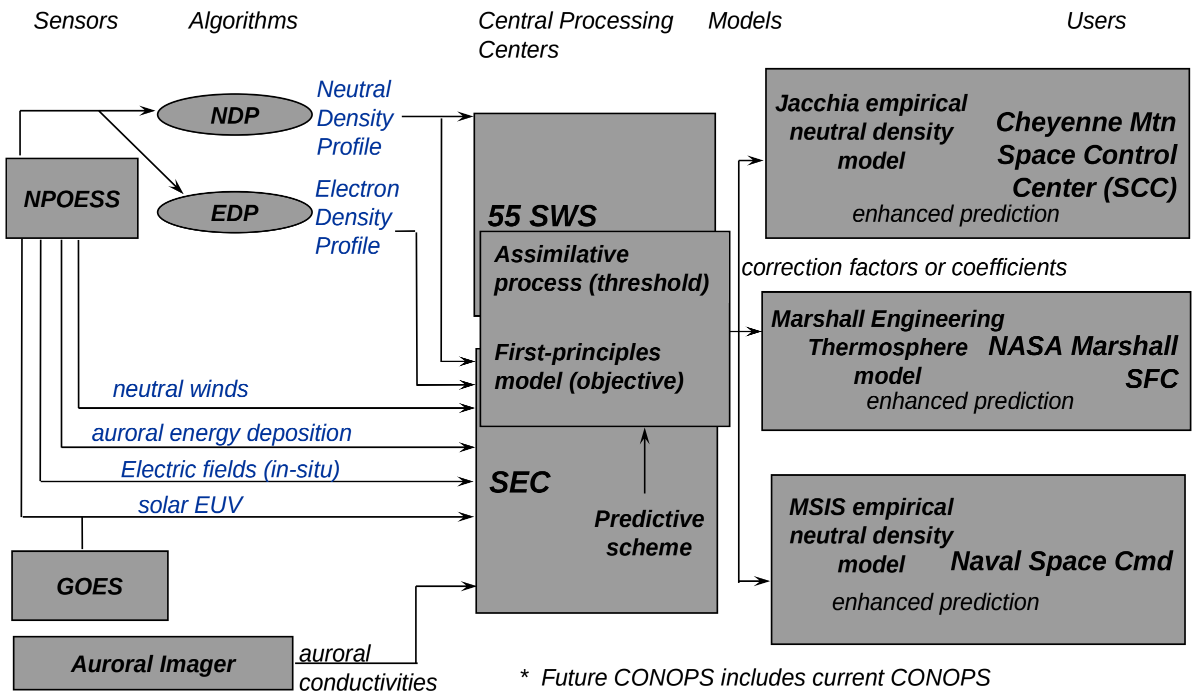

Figure 3A. Future Concept of Operations (1998 study)

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